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AGN feedback in clusters: shock and sound heating

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Observations support the view that feedback, in the form of radio outbursts from active nuclei in central galaxies, prevents catastrophic cooling of gas and rapid star formation in many groups and clusters of galaxies. Variations in jet power drive a succession of weak shocks that can heat regions close to the active galactic nuclei (AGN). On larger scales, shocks fade into sound waves. The Braginskii viscosity determines a well-defined sound damping rate in the weakly magnetized intracluster medium (ICM) that can provide sufficient heating on larger scales. It is argued that weak shocks and sound dissipation are the main means by which radio AGN heat the ICM, in which case, the power spectrum of AGN outbursts plays a central role in AGN feedback.

1 Introduction

X-ray observations of cool core clusters and groups have shown that radio outbursts from central AGN have large impacts on their hot atmospheres (reviewed in McNamara & Nulsen 2007). Radio outbursts originating near the event horizons of supermassive black holes deposit energy on spatial scales eight orders of magnitude larger. In the absence of a heat source, copious amounts of hot gas would be cooling to low temperatures and forming stars. Remarkably, powers of AGN outbursts are comparable to the powers needed to stop the gas from cooling, signalling that the mechanical power output of the AGN is governed by feedback (Bîrzan et al. 2004; Dunn & Fabian 2006; Rafferty et al. 2006; Croton et al. 2006; Sijacki & Springel 2006). Cooled or cooling gas can fuel AGN outbursts, while the outbursts heat the gas, affecting the fuel supply for subsequent outbursts. The high incidence of clusters with central cooling times less than 1 Gyr (Hudson et al. 2010) also argues for radio mode AGN feedback. While many processes might heat the ICM and prevent the gas from cooling, without feedback, it is all but impossible to account for the many systems with very short cooling times, while essentially no clusters are undergoing catastrophic cooling (McNamara & Nulsen 2012).

While the broad outline of the feedback cycle seems simple, very little of the detail is understood. In this article we focus on some processes that may heat the gas on scales comparable to the Bondi radius and larger. Apart from the discussion of viscosity, much of this material has been reviewed more thoroughly by McNamara & Nulsen (2012). We focus on the heating effects of weak shocks in section 2 and sound waves in section 3. In section 4 we consider how these processes operate together.

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2 Heating and outburst history

2.1 Adiabatic uplift is ineffective

To prevent the hot gas from cooling and forming stars, the key requirement is a heat source to replace heat lost by radiation. It should be emphasized that adiabatic uplift is ineffective at preventing gas from cooling. Extended filaments of cool, low entropy gas (e.g. Werner et al. 2010; Gitti et al. 2011) and heavy elements shed by evolving stars in the central galaxy (e.g. Million et al. 2010; Kirkpatrick et al. 2011) make a strong case for gas uplift in the wakes of radio lobes. Lifting gas outward adiabatically, into regions where the atmospheric pressure is lower, will generally extend its cooling time and so can help to delay the onset of cooling. However, for abundances and temperatures in the relevant range, the effect is modest. For example, for gas with solar abundances, starting at 3 keV and reducing the pressure adiabatically by a factor of $\simeq 88$ would reduce its temperature to 0.5 keV, but only increase its cooling time by $\simeq 36\%$. For gas with 0.5 solar abundances, the increase in cooling time is a little under a factor of 2, still well short of what is required to prevent the gas cooling in the long term (McNamara & Nulsen 2012).

Furthermore, unless the uplifted gas mixes with it surroundings, raising its entropy, it is negatively buoyant and will fall back to where it came from in about one free-fall time. That is generally much shorter than the cooling time, so the effect of lifting the gas is transient. Metals shed by cluster central galaxies are more extended than their stars, showing that they have diffused outward from where they were shed (Rebusco et al. 2005). However, if all the uplifted gas mixed effectively the mean diffusion rate would be far too high, so most of the gas must fall back almost to where it originates. Much of the energy needed to lift the gas is

then converted to kinetic energy and dissipated in the gas, providing a channel for heating (Gitti et al. 2011).

2.2 Weak shocks

The thermal energy of the gas within the volume V is

$$E_{\rm th} = 3/2 \int_V p \, dV, \qquad (1)$$

where p is its pressure. If the energy deposited by an AGN into this volume is comparable to or larger than $E_{\rm th}$, then the fractional pressure increase in V must be large to accommodate the extra energy. That would cause the region affected by the jet to expand supersonically, driving shocks into its surroundings and rapidly extending the region affected by the outburst. Similarly, shocks will be formed if the jet power exceeds $E_{\rm th}$ divided by the sound crossing time of V. Thus, the region affected by an outburst must contain a thermal energy prior to the outburst that is significantly larger than the outburst energy and also larger than the jet power times the sound crossing time of the region. Otherwise, shocks are generated. Based on simulations, Morsony et al. (2010) have found that, under the influence of cluster "weather" due to continuing infall, motion of substructures, etc., the radius of influence of the central AGN scales with the power of its jet, $P_{\rm jet}$, as $R_{\rm influence} \propto P_{\rm jet}^{1/3}$. The argument here suggests that this cannot be the whole story.

A number of systems, such as MS0735.6+7421 (McNamara et al. 2005) and NGC 5813 (Randall et al. 2011), show symmetric, large-scale shocks fronts that do not appear to be affected significantly by the cluster weather. Furthermore, in NGC 5813 (Randall et al. 2011) and M87 (Forman et al. 2007), there is clear evidence of multiple cavities and shocks. The nested shocks seen in these systems almost certainly require large and sustained variations in the power of the jet for their formation, consistent with other evidence of variations in jet power (e.g. Wise et al. 2007). Ripples in the Perseus ICM (Fabian et al. 2006) also indicate power variations (though sound may be driven in other ways, e.g. Sternberg & Soker 2009). Note that the small fluctuations seen at large distances from the cluster centre would have been considerably greater when they were launched in the region near NGC 1275. Power variations with shorter timescales and/or lower amplitude would be too weak to see now due to the combined effects of damping (section 3) and the decrease in amplitude with increasing radius. It is noteworthy that the two best observed systems with AGN outbursts, M87 and Perseus, show multiple weak shocks. Given the ubiquitous evidence of AGN variability on a broad range of timescales, this is probably the norm. As argued below, the power spectrum of AGN outbursts plays a critical role in AGN feedback by controlling the launching of shocks and sound waves.

Although the heating effect of individual weak shocks is minor, their cumulative impact need not be. The changes in thermal and kinetic energy associated with a weak shock may be substantial, but mostly move on with the shock. A small entropy increases, ΔS, that is cubic in the shock strength (Landau & Lifshitz 1959), is all that remains. The heat equivalent of the entropy jump is $\Delta Q = T \Delta S = E \, \Delta \ln K$, where $K = kT/n_{\rm e}^{2/3}$ is the entropy index and $\Delta \ln K$ is the jump of $\ln K$ in the shock. Expressed as a fraction of the gas thermal energy, $\Delta Q/E = \Delta \ln K$. For the innermost shock in M87, at a radius of $\simeq 0.8$ arcmin (3.7 kpc; Forman et al. 2007), the Mach number is $\simeq 1.38$, giving an equivalent heat input of only $\Delta Q/E \simeq 0.022$. There is a second shock at about twice the radius and a third shock that is several times more energetic at a radius of $\simeq 3$ arcmin. The shock spacings suggest that shocks of similar strength to the innermost shock are launched every ~ 2.5 Myr, while the cooling time of the gas at 0.8 arcmin is $\simeq 250$ Myr. The ~ 100 shocks launched during one cooling time would add heat $\Delta Q_{\rm tot}/E \simeq 100 \times 0.022 = 2.2$, more than enough to replace the energy radiated. These numbers are indicative only, but they show that repeated weak shocks alone can prevent gas near the centre of M87 from cooling (Nulsen et al. 2007). A similar argument has been made for weak shock heating in NGC 5813 (Randall et al. 2011).

Weak shocks can prevent gas cooling at the centres of two of the two nearest, best observed systems. The ripples in Perseus may well start as weak shocks launched from near the centre of NGC 1275, where they prevent the gas from cooling too. If the best observed systems are representative, weak shocks can be the primary channel for heating gas near the centres of all systems. Because shock strength declines with distance from the AGN and $\Delta \ln K$ depends steeply on shock strength, weak shocks become less effective at larger radii. However, as the shock strength decreases, sound dissipation increases in relative importance, probably taking over as the main heating channel, as outlined below. The efficiency of weak shock heating, measured by the fraction of shock energy converted to heat, is generally low, so that sound dissipation will often make a greater contribution to the total heating rate.

3 Plasma viscosity and sound heating

3.1 Plasma viscosity

Although the magnetic pressure in the ICM is typically only $\sim 1\%$ of the gas thermal pressure (Carilli & Taylor 2002), particle Larmor radii are ten or more orders of magnitude smaller than their mean free paths, keeping the particles tied rigidly to the magnetic field. As a consequence, transport processes in the ICM are poorly understood. This issue is worst for thermal conduction, since the heat flux depends on the structure of the magnetic field on scales comparable to the electron mean free path. The field may well vary on scales smaller than this, in which case the heat flux is not calculable in terms of local gas properties. Despite a great deal of work in this area, the role of thermal conduction in the ICM remains highly uncertain.

By contrast, viscous stresses are often determined locally. Fluid motions readily push the dynamically insignificant field around and, being frozen in, the field generally varies as the fluid moves. In a collisionless plasma, the magnetic moment, $mv_\perp^2/(2B)$, is conserved, where m is the particle mass, the strength of the magnetic field is B and the component of the particle velocity perpendicular to the field is $v_\perp$. Thus changes in the magnetic field cause corresponding changes in the transverse kinetic energy, $mv_\perp^2/2$, making the particle velocity distribution anisotropic. The proton-proton collision time is $\tau_{\rm pp} \simeq 700 (kT)^{3/2} n_{\rm p}^{-1}$ yr, where the temperature, kT, is in keV and the proton density, $n_{\rm p}$, is in ${\rm cm}^{-3}$. Collisional relaxation can generally suppress most of the anisotropy caused by fluid motions, leaving only a small residual effect. Anisotropy in the velocity distribution implies anisotropy in the pressure, which can be expressed as the difference between the transverse and mean pressures, $\Delta = p_\perp - p$. When collisional relaxation is fast compared to the rate of change in B, i.e. $\tau_{\rm ii} |dB/dt| \ll B$, where $\tau_{\rm ii}$ is the ion-ion collision time, the pressure anisotropy is given by (e.g. Kunz et al. 2012)

$$\Delta = \tau_{\rm ii} p_{\rm i} \left(\mathbf{bb} : \nabla \mathbf{v} - \frac{1}{3} \nabla \cdot \mathbf{v} \right), \qquad (2)$$

where $p_{\rm i}$ is the ion pressure, $\mathbf{b}$ is the direction of the magnetic field and $\mathbf{v}$ is the fluid velocity. The viscous stress tensor, which is minus the anisotropic part of the total stress tensor, is then

$$\mathbf{T} = \Delta (3\mathbf{bb} - \mathbf{1}), \qquad (3)$$

where $\mathbf{1}$ is the 3×3 unit matrix. This is the Braginskii (1965) form of the viscous stress tensor for a magnetized plasma. Anisotropy generated by motion parallel and perpendicular to the magnetic field simply reflects work done on or by the components of the particle velocities through the corresponding particle pressures, $p_\perp$ or $p_\parallel = 3p - 2p_\perp$. In a uniform magnetic field parallel to the z axis, with gas motions only parallel the field, T_{zz} must have the same value as it does in the absence of a magnetic field. This requires $\tau_{\rm ii} p_{\rm i}$ to equal the viscosity of an unmagnetized plasma, i.e. the "Spitzer" viscosity. Thus, although the viscous stresses depend on the direction of the magnetic field, they are similar in magnitude to the stresses in the absence of a magnetic field.

3.2 Sound heating

Calculation of sound damping for a magnetized ICM is much the same as in the field free case. We assume that the unperturbed magnetic field is uniform and parallel to the z axis. For sound with wavevector $\mathbf{k} = (k_x, k_y, k_z)$, the damping rate of the amplitude is

$$\frac{1}{6} \nu k^2 \left(1 - 3 \frac{k_z^2}{k^2} \right)^2, \qquad (4)$$

where $\nu = \tau_{\rm ii} p_{\rm i} / \rho$ is the kinematic viscosity and ρ is the gas density. For sound waves travelling parallel to the magnetic field ($k_z^2 = k^2$), this is identical to the damping rate with no magnetic field, $2\nu k^2/3$, as we should expect. For sound travelling perpendicular to the field ($k_z = 0$), the damping rate is $\nu k^2/6$, a factor of 4 smaller. Note that for $k_z^2 = k^2/3$, i.e. for sound waves inclined at $\simeq 54.7^\circ$ to the magnetic field, the damping rate is zero. In this direction sound waves have the same effect on $p_\perp$ and $p_\parallel$, so they generate no anisotropy, hence no viscous damping.

Due to cluster weather, the field is likely to be fairly chaotic, with structure on scales down to 10 kpc or less (e.g. Govoni et al. 2010). If the field is isotropic on average, we can average the damping rate (4) over the sphere to obtain the mean value of $2\nu k^2/15$, one fifth of the damping rate with no magnetic field. Fabian et al. (2005) have shown that viscous damping of sound is a viable mechanism to prevent gas cooling in the Perseus cluster and Abell 2199. Their models used a viscous damping rate that is one half of the mean rate calculated here. As they discuss, the power spectrum of the AGN outbursts is critical for the heating rate, since it controls the spectrum of sound generated by outbursts and the dissipation rate is sensitive to the frequency. Corresponding to the average damping rate, the dissipation length for sound power is

$$120 \left(\frac{\omega}{\omega_{\rm s}} \right)^{-2} \left(\frac{n_{\rm e}}{0.03\ {\rm cm}^{-3}} \right) \left(\frac{kT}{5\ {\rm keV}} \right)^{-1}\ {\rm kpc}, \qquad (5)$$

where the angular frequency unit, $\omega_{\rm s} = 2.36 \times 10^{-14}\ {\rm s}^{-1}$, gives a wavelength 10 kpc for a gas temperature of 5 keV (cf. Fabian et al. 2005). This is comparable to the size of cluster cool cores. If the thermal conductivity is close to its field free value, conduction would boost the dissipation rate significantly. However, viscous dissipation alone appears sufficient to heat the ICM in Perseus and Abell 2199.

Schekochihin et al. (2005) note that, when the anisotropy falls outside the range $-2p_B/3 < \Delta < p_B/3$, for $p_B = B^2/(8\pi)$, the plasma is prone to firehose or mirror instabilities that grow much faster than viscous damping. For $p_B \ll p$, as in clusters, this condition is more restrictive than the one preceding equation (2). It requires $\omega \tau_{\rm ii} A \lesssim 0.5 p_B/p$, where A is the amplitude of the fractional density fluctuations. If the anisotropy did get too large, sound damping could be much faster than the viscous rate and sound heating even more effective — probably too effective, although some sound energy would then be converted to magnetic field rather than being thermalized (Schekochihin et al. 2005).

4 Discussion

Variations in the power of the jet launched from the AGN initiate a succession of weak shocks that originate from somewhere near the Bondi radius (disregarding the small amount of gas within the Bondi sphere). The distribution of gas close to the radio lobes is generally far from spherical and the shock strength varies over the surface of spheres (e.g. Forman et al. 2005; Mendygral et al. 2012). However, shock strength generally decreases radially. As the shocks weaken,

at some point they can be regarded as sound waves. Although the power spectrum of the sound is far from monochromatic, for the purpose of discussion here, we assume that there is a representative frequency, ω, where $2\pi/\omega$ is typical of the time interval between shocks.

Heating by weak shocks (section 2.2) depends on the fractional pressure jump, $\delta p/p$, as $(\delta p/p)^3$, whereas sound damping heats the gas at a rate proportional to the square of the sound amplitude. As a result, shock heating is more significant at small radii where the pressure disturbance is larger, but as the disturbance decreases with increasing radius, sound dissipation will overtake it at some point. If the mean kinematic viscosity is $\nu/5$ (section 3.2) and the fractional amplitude of the sound pressure disturbance is related to the pressure jump by $A_p = 0.5\delta p/p$, the ratio of the shock heating rate to the sound heating rate is (McNamara & Nulsen 2007)

$$\frac{2s^2}{\pi\nu\omega}\left(\frac{\delta p}{p}\right) \simeq 12.6 \left(\frac{\omega}{\omega_{\rm s}}\right)^{-1}\left(\frac{n_{\rm e}}{0.03\,{\rm cm}^{-3}}\right)\left(\frac{kT}{5\,{\rm keV}}\right)^{-3/2}\left(\frac{\delta p}{p}\right) \quad (6)$$

in the units of equation (5). If the entropy or the effective frequency is high (for wavelengths comparable to the proton mean free path or smaller), sound damping might rival shock heating, even for $\delta p/p \sim 1$, but low entropies in cool cores favour weak shock heating. Weak shock heating probably dominates close to the Bondi radius, while sound damping is more effective on larger scales. For both processes, the power spectrum of AGN outbursts plays a central role in determining the heating rate. Clearly, we need to understand how that is governed.

5 Conclusions

Low rates of gas cooling and star formation in the central galaxies of many groups and clusters are best explained by feedback from radio AGN. This view is supported by observations of the impacts of radio outbursts in hot atmospheres. Jet powers vary significantly on a wide range of timescales, causing a succession of shocks to be launched from near the radio lobes. The shocks weaken into sound waves on larger scales. For the best observed, nearby systems, weak shocks provide sufficient heat near the AGN to prevent gas from cooling.

In contrast to thermal conduction, the Braginskii viscosity generally provides a well-defined, local, viscous stress that only depends on the direction of the magnetic field in the weakly magnetized ICM. It determines a viscous damping rate for sound that is a factor of five smaller than that for unmagnetized plasma when the field is isotropic on average. This level of sound damping is sufficient to prevent gas from cooling throughout the cool core of the Perseus cluster. The combination of weak shock heating on small scales and sound damping on larger scales plausibly provides the primary means by which AGN energy heats the ICM and prevents gas from cooling. If so, the power spectrum of AGN outbursts plays a central role in AGN feedback and needs to be better understood.

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References

Bîrzan, L., Rafferty, D.A., McNamara, B.R., Wise, M.W., Nulsen, P.E.J.: 2004, ApJ 607, 800
Braginskii, S.I.: 1965, Reviews of Plasma Physics 1, 205
Carilli, C.L., Taylor, G.B.: 2002, ARA&A 40, 319
Croton, D.J., Springel, V., White, S.D.M., et al.: 2006, MNRAS 365, 11
Dunn, R.J.H., Fabian, A.C.: 2006, MNRAS 373, 959
Fabian, A.C., Reynolds, C.S., Taylor, G.B., Dunn, R.J.H.: 2005, MNRAS 363, 891
Fabian, A.C., Sanders, J.S., Taylor, G.B., et al.: 2006, MNRAS 366, 417
Forman, W., Jones, C., Churazov, E., et al.: 2007, ApJ 665, 1057
Forman, W., Nulsen, P., Heinz, S., et al.: 2005, ApJ 635, 894
Gitti, M., Nulsen, P.E.J., David, L.P., McNamara, B.R., Wise, M.W.: 2011, ApJ 732, 13
Govoni, F., Dolag, K., Murgia, M., et al.: 2010, A&A 522, A105
Hudson, D.S., Mittal, R., Reiprich, T.H., et al.: 2010, A&A 513, A37
Kirkpatrick, C.C., McNamara, B.R., Cavagnolo, K.W.: 2011, ApJ 731, L23
Kunz, M.W., Bogdanović, T., Reynolds, C.S., Stone, J.M.: 2012, ApJ 754, 122
Landau, L.D., Lifshitz, E.M.: 1959, "Course of theoretical physics" 6, "Fluid Mechanics," Oxford: Pergamon Press
McNamara, B.R., Nulsen, P.E.J.: 2007, ARA&A 45, 117
McNamara, B.R., Nulsen, P.E.J.: 2012, New Journal of Physics 14, 055023
McNamara, B.R., Nulsen, P.E.J., Wise, M.W., et al.: 2005, Nature 433, 45
Mendygral, P.J., Jones, T.W., Dolag, K.: 2012, ApJ 750, 166
Million, E.T., Werner, N., Simionescu, A., et al.: 2010, MNRAS 407, 2046
Morsony, B.J., Heinz, S., Brüggen, M., Ruszkowski, M.: 2010, MNRAS 407, 1277
Nulsen, P.E.J., Jones, C., Forman, W.R., et al.: 2007, "Heating versus Cooling in Galaxies and Clusters of Galaxies," ESO Astrophysics Symposia, Berlin: Springer, 210
Rafferty, D.A., McNamara, B.R., Nulsen, P.E.J., Wise, M.W.: 2006, ApJ 652, 216
Randall, S.W., Forman, W.R., Giacintucci, S., et al.: 2011, ApJ 726, 86
Rebusco, P., Churazov, E., Böhringer, H., Forman, W.: 2005, MNRAS 359, 1041
Schekochihin, A.A., Cowley, S.C., Kulsrud, R.M., Hammett, G.W., Sharma, P.: 2005, ApJ 629, 139
Sijacki, D., Springel, V.: 2006, MNRAS 366, 397
Sternberg, A., Soker, N.: 2009, MNRAS 395, 228
Werner, N., Simionescu, A., Million, E.T., et al.: 2010, MNRAS 407, 2063
Wise, M.W., McNamara, B.R., Nulsen, P.E.J., Houck, J.C., David, L.P.: 2007, ApJ 659, 1153

